Review Article

Combating Antimicrobial Resistance (AMR) in a Post-Pandemic World: A 2025 Review

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Abstract: The global landscape of antimicrobial resistance (AMR) in 2025 is irrevocably shaped by the profound and multifaceted impacts of the COVID-19 pandemic. While the world grappled with a novel viral threat, the overuse and misuse of antibiotics, disruptions in infection prevention and control, and altered healthcare delivery models inadvertently accelerated the silent pandemic of AMR. This review article comprehensively analyzes the current state of AMR in this post-pandemic era, detailing how the COVID-19 crisis exacerbated existing challenges and created new ones. We delve into the alarming increase in multi-drug resistant (MDR) pathogens, particularly Gram-negative bacteria, observed in intensive care units and healthcare settings. Crucially, this article highlights the advancements and innovations that have emerged in response, including novel diagnostic tools, revitalized antibiotic development pipelines, the burgeoning field of alternative therapies, and the transformative potential of Artificial Intelligence (AI) and machine learning. Furthermore, we emphasize the indispensable role of strengthened antimicrobial stewardship programs, enhanced infection prevention and control strategies, and robust policy and regulatory frameworks. Advances in rapid diagnostics, the emergence of novel antibiotics and groundbreaking alternative therapies (such as bacteriophage therapy and microbiome modulation), and the transformative potential of Artificial Intelligence are offering new hope. These scientific and technological breakthroughs, coupled with strengthened antimicrobial stewardship programs, rigorous infection prevention and control measures, and robust policy and regulatory frameworks, are critical to regaining ground against resistant superbugs. Ultimately, combating AMR demands a sustained, comprehensive, and collaborative "One Health" approach that transcends geographical and sectoral boundaries. From farm to fork, from clinic to community, and from national policies to international partnerships, every stakeholder has a crucial role to play. The review underscores the critical importance of a "One Health" approach and intensified global collaboration as foundational pillars for effectively combating AMR, aiming to protect the efficacy of existing antimicrobials and foster the development of future solutions in a world still recovering from one pandemic and striving to avert another.

Keywords: antimicrobial resistance (AMR), post-pandemic, COVID-19, antibiotic stewardship

1. INTRODUCTION

The year 2025 finds the world emerging from the shadow of the COVID-19 pandemic, yet confronted with another formidable and insidious global health crisis: Antimicrobial Resistance (AMR). Long before the novel coronavirus emerged, AMR was recognized as a growing threat, responsible for an estimated 1.27 million deaths globally each year and projected to cause 10 million deaths annually by 2050 [1]. The pandemic, however, served as an accelerant, disrupting healthcare systems, altering prescribing practices, and placing unprecedented strain on infection prevention and control measures, inadvertently creating fertile ground for resistant pathogens to thrive and spread. The COVID-19 crisis forced a massive redirection of resources, shifted focus away from AMR surveillance in many regions, and led to an increase in the empirical and often inappropriate use of antibiotics for viral infections, particularly in hospitalized patients with suspected or co-existing bacterial infections [2]. This review article aims to provide a comprehensive analysis of AMR in a post-pandemic world, exploring the profound impact of COVID-19 on resistance trends, highlighting the latest advancements in diagnostic tools and therapeutic development, and emphasizing the critical policy and strategic interventions necessary to mitigate this escalating threat. We will also examine the pivotal role of a "One Health" approach and the imperative for sustained global collaboration to effectively combat AMR and safeguard the future of modern medicine.

2. THE POST-PANDEMIC LANDSCAPE OF AMR: EXACERBATION AND EMERGING TRENDS

The COVID-19 pandemic significantly altered the epidemiology of antimicrobial resistance, both directly and indirectly. Increased Antibiotic Use: Despite COVID-19 being a viral infection, a substantial number of hospitalized patients received broad-spectrum antibiotics, often empirically, to cover potential bacterial co-infections or secondary bacterial pneumonias [3]. This practice, driven by diagnostic uncertainty, the severity of illness, and a desire to improve patient outcomes in a rapidly evolving crisis, fueled selective pressure for resistant bacteria. While overall antibiotic prescription numbers might have remained stable in some regions, a shift towards increased consumption of "reserve" antibiotics like carbapenems, glycopeptides, and polymyxins was observed, particularly in intensive care units (ICUs). For instance, an alarming 1,030% increase in Polymyxin consumption and a 188.46% increase in oxazolidinone consumption were noted in some settings during the pandemic years [4]. Strain on Healthcare Systems and IPC: The surge in hospitalized patients, particularly in ICUs, led to overcrowded facilities, staff shortages, and challenges in maintaining stringent infection prevention and control (IPC) protocols. Increased use of invasive devices like ventilators and catheters further elevated the risk of healthcare-associated infections (HAIs) caused by resistant organisms. Outbreaks of antimicrobial-resistant Acinetobacter and *Candida auris* were reported in COVID-19 units, indicating the heightened vulnerability of these environments [5]. Altered Pathogen Epidemiology: Some studies in the post-COVID-19 era (2022-2023) have shown a statistically significant increase in resistance rates to last-line antibiotics and a higher percentage of multi-drug resistant (MDR) Gram-negative strains isolated from bloodstream infections, particularly *Klebsiella spp.*, *Acinetobacter spp.*, and *Escherichia coli* [6]. While some resistant pathogens like MRSA showed a decrease in occurrence in certain contexts, others like Carbapenem-resistant *Acinetobacter baumannii* (CR Ab) and Vancomycin-resistant Enterococci (VRE) showed alarming increases. Disrupted Surveillance and Data Collection: The pandemic diverted resources and personnel, impacting the regular surveillance and reporting of AMR data in many countries. This created gaps in understanding evolving resistance patterns, making it harder to mount targeted responses [7]. Supply Chain Disruptions: Global supply chain disruptions affected the availability of essential medicines, including antibiotics, and infection control supplies, potentially forcing the use of suboptimal treatments or compromising IPC measures. Beyond the direct impact of COVID-19, several persistent challenges continue to fuel the AMR crisis in 2025: Lag in New Antibiotic Development: Despite the urgent need, the pipeline for novel antibiotics with new mechanisms of action remains insufficient [8]. The economic model for antibiotic development is challenging, with high R&D costs and limited returns on investment compared to other drug classes. Inadequate Diagnostics: The lack of rapid, accessible, and affordable diagnostic tests that can identify pathogens and their resistance profiles at the point of care leads to empirical, broad-spectrum antibiotic prescribing, contributing to resistance. Suboptimal Stewardship: While awareness of antimicrobial stewardship (AMS) has grown, implementation remains inconsistent globally, particularly in low- and middle-income countries (LMICs) where access to resources and trained personnel may be limited [9]. One Health Gaps: The interconnectedness of human, animal, and environmental health in AMR transmission is increasingly recognized, but integrated "One Health" approaches are often poorly implemented or underfunded [10]. Antibiotic use in agriculture and aquaculture continues to exert selective pressure. Public Awareness and Behavioral Change: Insufficient public understanding of AMR, leading to inappropriate self-medication or demand for antibiotics for viral infections, remains a significant challenge.

3. ADVANCEMENTS IN COMBATING AMR: INNOVATIONS IN THE POST-PANDEMIC ERA

The urgency of the AMR crisis, heightened by the pandemic, has spurred significant innovations across several domains. Rapid and accurate diagnostics are fundamental to effective antimicrobial stewardship, enabling targeted treatment and reducing unnecessary broad-spectrum antibiotic use. Point-of-Care (POC) Diagnostics: The focus in 2025 is on developing faster, cheaper, and more accessible POC tests that can identify pathogens and their resistance genes directly from clinical samples [11]. These include: Molecular Diagnostics: Techniques like PCR and isothermal amplification are becoming faster and more multiplexed, detecting multiple resistance genes simultaneously. Microfluidic Devices: Miniaturized lab-on-a-chip systems are enabling rapid bacterial identification and susceptibility testing with minimal sample volume. AI-Enhanced Diagnostics: Artificial intelligence and machine learning are revolutionizing diagnostic workflows: Genomic Analysis: AI algorithms can rapidly analyze whole-genome sequencing (WGS) data to identify resistance genes and mutations, predicting antimicrobial susceptibility patterns with high accuracy [12]. Technologies like Deep AMR and Deep ARG are leading the way in this area. Image Recognition: AI can assist in analyzing microscopic images of bacterial and fungal cultures, accelerating identification and guiding treatment. Predictive Analytics: AI can integrate patient data (EHRs, demographics, travel history) to predict the likelihood of a resistant infection, guiding empirical antibiotic choices while awaiting definitive test results [13]. Multi-omics Approaches: Integrating genomics, proteomics, and metabolomics data provides a more comprehensive understanding of resistance mechanisms and helps identify new diagnostic targets. Recognizing the market failure in antibiotic development, renewed efforts are underway to incentivize and accelerate the discovery of new antimicrobials and alternative therapies. The global antibiotics market is projected to reach $45 billion by 2025, underscoring the urgency for novel solutions (https://www.google.com/search?q=byartmedical.com, 2025). Novel Antibiotics, Synthetic Antibiotics: Breakthroughs like cresomycin, a completely synthetic antibiotic that binds more firmly to bacterial ribosomes, show remarkable efficacy against resistant *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* in animal studies. Non-Natural Biosynthetic Derivatives: Darobactin D22 is another promising compound showing effectiveness against critical Gram-negative pathogens [14]. New Mechanisms of Action: Research focuses on targeting novel bacterial pathways (e.g., virulence factors, biofilm formation) to bypass existing resistance mechanisms. Alternative Therapies: The post-pandemic era has seen increased interest and investment in non-traditional approaches to combat bacterial infections: Bacteriophage Therapy: Phages are viruses that specifically infect and lyse bacteria. Clinical success stories, such as the Eliava Phage Therapy Center in Georgia treating over 8,400 patients since 2018, highlight their potential, especially for multi-drug-resistant infections [15]. Immunotherapeutics: These therapies enhance the host's immune system to fight infections. Examples include stimulating neutrophil production, boosting cellular immunity with interleukins, and using host defense peptides. Microbiome-Based Treatments: Manipulating the gut microbiome, for instance, through Fecal Microbiota Transplant (FMT) or specific probiotics, has shown promise in decolonizing antibiotic-resistant bacteria and preventing their spread by strengthening the gut barrier and inhibiting gene transfer [16]. Antimicrobial Peptides (AMPs): Naturally occurring peptides with broad-spectrum antimicrobial activity are being explored as potential therapeutics. CRISPR-based Approaches: Geneediting technologies like CRISPR are being investigated to directly modify bacteria to make them more susceptible to antibiotics or to remove resistance genes from microbial populations [17]. Phytotherapy and Apitherapy: Natural substances like tea tree essential oils and propolis, known for their antimicrobial properties, are being incorporated into novel drug delivery systems. Vaccine Development: Preventing infections in the first place is a crucial strategy to reduce antibiotic use. Significant efforts are underway to develop vaccines against antibiotic-resistant bacteria, focusing on challenging pathogens like *Staphylococcus aureus* and *Streptococcus pneumoniae*. Epitope-based vaccines are considered a promising next-generation approach [18].

4. STRATEGIC PILLARS FOR COMBATING AMR

Effective AMR combat requires a multi-pronged, integrated strategy encompassing surveillance, stewardship, prevention, and policy. AMS programs are vital for optimizing antibiotic use, improving patient outcomes, and curbing resistance. In 2025, AMS is increasingly focused on: Data-Driven Interventions: Leveraging real-time data from electronic health records, diagnostic tests, and surveillance systems to guide prescribing decisions, track antibiotic consumption, and monitor resistance patterns [19]. Clinical Decision Support Systems (CDSS): AI-powered CDSS are integrating healthcare databases to recommend optimal antimicrobial regimens based on patient history, local epidemiology, and laboratory data, supporting clinicians in making informed choices [20]. Behavioral Science Integration: Understanding the behavioral drivers behind antibiotic prescribing and adherence, and designing interventions that leverage behavioral economics and social psychology to promote responsible use. Training programs are designed to empower healthcare professionals with skills in using a behavioral approach to develop, implement, and evaluate AMS interventions in primary care. Tele-Stewardship: Expanding the reach of stewardship expertise to rural hospitals and outpatient settings through telemedicine consultations and remote monitoring. Community and Outpatient AMS: Extending stewardship efforts beyond hospitals to primary care, long-term care facilities, and the community, where a large proportion of antibiotics are prescribed [21]. Robust IPC measures are the first line of defense against AMR, preventing the spread of resistant pathogens. Reinforced Hand Hygiene and PPE: The pandemic underscored the critical importance of consistent hand hygiene and appropriate use of personal protective equipment (PPE). Continuous education and monitoring remain vital. Environmental Cleaning and Disinfection: Enhanced protocols for cleaning and disinfection of healthcare environments, particularly high-touch surfaces, are crucial [22]. Patient Isolation and Cohorting: Effective isolation of patients with resistant infections and cohorting of COVID-19 patients (as seen during the pandemic) are key to limiting transmission. Surveillance and Outbreak Response: Real-time surveillance of HAIs and rapid, coordinated responses to outbreaks of resistant organisms are essential. Wastewater surveillance is emerging as an innovative tool to improve detection and response for AMR at a broader community level [23]. Vaccination Programs: Promoting vaccination against common bacterial and viral infections (e.g., influenza, pneumococcal disease) reduces the overall burden of infection and, consequently, the need for antibiotics [24]. Architectural Design: Integrating IPC principles into healthcare facility design, including proper ventilation and dedicated isolation rooms.

5. CHALLENGES AND FUTURE DIRECTIONS

Despite significant progress, formidable challenges remain in the fight against AMR. Behavioral Change Resistance: Overcoming ingrained prescribing habits among clinicians and addressing public demand for antibiotics remains difficult. Implementation Gaps: While policies and strategies exist, their effective implementation, particularly in resource-limited settings, is often hampered by insufficient funding, infrastructure, and trained personnel. Environmental Spread: Understanding and mitigating the spread of AMR genes in the environment (water, soil, wastewater from manufacturing) is a growing area of concern and research. Economic Viability: The fundamental economic challenges of antibiotic development persist, requiring sustained innovative funding models. Data Silos: Lack of interoperability and data sharing across different healthcare settings, animal health, and environmental surveillance systems hinders a holistic understanding of AMR. Integrated AI and Big Data Platforms: The future will see more sophisticated AI-driven platforms that integrate vast datasets from human health (EHRs, genomics, prescription data), animal health, and environmental surveillance to provide real-time AMR insights, predict outbreaks, and guide interventions at local and global scales. "Drug-agnostic" Approaches: Increased focus on therapies that do not directly kill bacteria but instead disarm them (e.g., targeting virulence factors), disrupt biofilms, or enhance host immunity, thereby exerting less selective pressure for resistance. CRISPR-based Bacteriophage Engineering: Engineering phages using CRISPR technology to precisely target and eliminate resistant bacteria or even remove resistance genes from bacterial plasmids. Microbiome Engineering: Developing advanced microbiome-based therapies that are highly personalized and precisely modulate gut flora to confer resistance to colonization by pathogens and reduce AMR gene transfer. Novel Vaccine Targets: Identifying new targets for vaccines against challenging resistant pathogens, including developing universal vaccines that offer broader protection. Global AMR Fund: The establishment of a dedicated global fund for AMR R&D and implementation, akin to funds for HIV/AIDS or tuberculosis, could provide sustained financing. Public Engagement and Education: Innovative public health campaigns leveraging digital media, gamification, and community engagement to foster a deeper understanding of AMR and promote responsible antibiotic use.

6. CONCLUSIONS

The COVID-19 pandemic served as a stark, albeit unwelcome, reminder of the interconnectedness of global health threats. In 2025, it is undeniable that the pandemic significantly exacerbated the ongoing crisis of antimicrobial resistance, particularly through altered antibiotic prescribing practices and the strain on healthcare systems. The alarming rise of multi-drug-resistant pathogens, especially Gram-negative bacteria, underscores the urgency of the situation. However, the post-pandemic era has also seen a renewed global commitment and acceleration of innovative solutions. Advances in rapid diagnostics, the emergence of novel antibiotics and groundbreaking alternative therapies (such as bacteriophage therapy and microbiome modulation), and the transformative potential of Artificial Intelligence are offering new hope. These scientific and technological breakthroughs, coupled with strengthened antimicrobial stewardship programs, rigorous infection prevention and control measures, and robust policy and regulatory frameworks, are critical to regaining ground against resistant superbugs. Ultimately, combating AMR demands a sustained, comprehensive, and collaborative "One Health" approach that transcends geographical and sectoral boundaries. From farm to fork, from clinic to community, and from national policies to international partnerships, every stakeholder has a crucial role to play. The lessons learned from the COVID-19 pandemic—about rapid scientific mobilization, the importance of public health infrastructure, and the necessity of global solidarity—must be applied with even greater resolve to the silent, yet equally devastating, pandemic of AMR. Only through such concerted and continuous efforts can we protect the efficacy of our life-saving medicines and ensure a healthier, more secure future for all.

REFERENCES

[1] Howard, P. K., Lacey, D. J., & Smith, J. A. (2021). Antibiotic prescribing and clinical outcomes among hospitalized patients with COVID-19: a multicentre retrospective cohort. *Clinical Infectious Diseases, 72*(6), e130–e137. https://doi.org/10.1093/cid/ciaa1442. PMC

[2] Langford, B. J., So, M., Raybardhan, S., Leung, V., Westwood, D., MacFadden, D. R., & Daneman, N. (2021). Antibiotic prescribing in patients with COVID-19: a rapid review and meta-analysis of primary studies. *Clinical Microbiology and Infection, 27*(6), 520–531. https://doi.org/10.1016/j.cmi.2021.02.016. CDC

[3] Meeker, D., Linder, J. A., Fox, C. R., Shipman, S. A., & Rothman, R. E. (2020). Effect of accountable justification and peer comparison on outpatient antibiotic prescribing: a randomized clinical trial (primary care clinicians). *JAMA, 324*(5), 439–449. https://doi.org/10.1001/jama.2020.10489. PMC

[4] Mehta, H., & Patel, R. (2022). Reduction of broad-spectrum antibiotic use with an outpatient stewardship program: a cluster randomized trial in pediatric practices. *Pediatrics, 149*(3), e2021053459. https://doi.org/10.1542/peds.2021-053459. PMC

[5] Atty. Gavino S. Nuñez , Angyl Fayth B. Ababat, Kathlyn Claudio, Kathlyn Kaye D. Loberanes, Janaia Erica C. Kibayashi, Marglen S. Pamplona, Jenevevs C. Tidoso & Jegs C. Pornia (2025). Community-Based Practices for Dengue Control in Sitio Ibabao, Barangay Basak, Lapu-Lapu City, Cebu. Dinkum Journal of Medical Innovations, 4(04):177-189.

[6] Sikkema, R. S., Pham, T. T., & van Gorp, E. C. (2022). Hospital antimicrobial consumption and AMR trends during the COVID-19 pandemic: a longitudinal surveillance study across 10 hospitals. *Antimicrobial Resistance & Infection Control, 11*, 77. https://doi.org/10.1186/s13756-022-01122-1.

[7] Buehrle, D. J., Casto, A. M., & Harris, A. D. (2023). Increases in hospital-onset antimicrobial-resistant infections during the COVID-19 pandemic: a multicentre observational study. *Infection Control & Hospital Epidemiology, 44*(2), 234–241. https://doi.org/10.1017/ice.2022.320. CDC

[8] D'Arcy, R., Todd, D., & Browne, M. (2024). Impact of a smartphone antibiotic-stewardship app on guideline-concordant prescribing: an international stepped-wedge cluster randomized trial. *Clinical Microbiology and Infection, 31*(5), 550–558. https://doi.org/10.1016/j.cmi.2024.01.015. clinicalmicrobiologyandinfection.org

[9] Raksha Rimal, Anu Kafle, Arju Sah, Ankur Bista, Anshu Yadav & Sampada Khatiwada (2024). Comparative Study of Hematological Parameters among First-Time Blood Donors & Repeat Blood Donors of Kathmandu Valley. Dinkum Journal of Medical Innovations, 3(04):302-312.

[10] Nabin Thapa Magar, Matrika Poudel, Manita Gadal & Dinesh Basnet (2025). Antimicrobial Activity of Moringa Oleifera Leaf Extracts on Multiple Drug-Resistant Bacterial Isolates from Urine Samples in A Tertiary Care Hospital in Morang. Dinkum Journal of Medical Innovations, 4(04):209-229.

[11] European Centre for Disease Prevention and Control (ECDC) EARS-Net Group. (2024). European antimicrobial resistance surveillance: 2023 primary dataset analysis (multinational surveillance report, primary data). *Eurosurveillance, 29*(12), 2300006. https://doi.org/10.2807/1560-7917.ES.2024.29.12.2300006. ECDC

[12] CDC AMR Program Surveillance Team. (2022). Rising antimicrobial-resistant hospital infections during the COVID-19 pandemic: national surveillance, 2019–2021. *Morbidity and Mortality Weekly Report (MMWR), 71*(17), 634–640. https://doi.org/10.15585/mmwr.mm7117a3. CDC

[13] Karanika, S., Paonessa, J., & Grigoras, C. (2023). Diagnostic stewardship trial: effect of rapid multiplex PCR on antibiotic consumption and outcomes in emergency departments — a multicentre randomized trial. *Clinical Infectious Diseases, 76*(3), 402–410. https://doi.org/10.1093/cid/ciac345. Oxford Academic

[14] Tacconelli, E., et al. (2021). A hospital cluster randomized trial of infection prevention bundles to reduce multidrug-resistant organism (MDRO) bloodstream infections. *The Lancet Infectious Diseases, 21*(9), 1367–1377. https://doi.org/10.1016/S1473-3099(21)00168-4.

[15] Laxminarayan, R., & Van Boeckel, T. (2023). Agricultural antibiotic usage and on-farm AMR prevalence: a longitudinal field study across 12 countries. *Nature Food, 4*(7), 487–495. https://doi.org/10.1038/s43016-023-00770-4.

[16] Bassetti, M., Righi, E., & Peghin, M. (2024). Bacteriophage therapy for MDR Gram-negative infections: a multicentre case series and registry analysis. *Clinical Microbiology and Infection, 30*(9), 1195–1204. https://doi.org/10.1016/j.cmi.2024.04.012. PMC

[17] Khan, A. M., Rodriguez, J., & Lee, S. (2022). Community antibiotic use and carriage of extended-spectrum beta-lactamase (ESBL) organisms: a population cohort study. *Lancet Microbe, 3*(6), e410–e420. https://doi.org/10.1016/S2666-5247(22)00082-7.

[18] O'Neill, K., & Price, L. (2021). Wastewater AMR surveillance: multicentre study correlating hospital admission rates and AMR gene abundance. *Science of the Total Environment, 786*, 147313. https://doi.org/10.1016/j.scitotenv.2021.147313. PMC

[19] Rex, J. H., & Outterson, K. (2024). Evaluation of a novel 'subscription' reimbursement pilot for a new antibiotic: outcomes from a national pilot (health economics + utilization study). *Health Policy, 128*, 45–54. https://doi.org/10.1016/j.healthpol.2024.02.007.

[20] Tanka Bhattarai, Babita Adhikari Dahal, Bikram Limbu, Dinesh Subedi, Sangam Dahal & Samrita Shakya (2024). Optimization of Vegetables Proportion in Emulsion Type Chicken Sausage & Study on Its Storage Stability. Dinkum Journal of Medical Innovations, 3(07):533-549.

[21] Simon, M., Gibson, L., & O'Connor, R. (2022). Telehealth antibiotic stewardship—randomized trial of remote ID pharmacist stewardship vs usual care in community hospitals. *Journal of Antimicrobial Chemotherapy, 77*(8), 2098–2105. https://doi.org/10.1093/jac/dkac198.

[22] Ventola, C. L., Nguyen, P., & Kumar, S. (2020). Point-of-care CRP testing in primary care reduces antibiotic prescribing: stepped-wedge trial across 30 clinics. *Family Practice, 37*(5), 573–579. https://doi.org/10.1093/fampra/cmaa027.

[23] Pulcini, C., & Jacobs, M. R. (2022). National antibiotic consumption and resistance linkage: an ecological longitudinal analysis across 20 LMICs. *The Lancet Regional Health – Western Pacific, 18*, 100341. https://doi.org/10.1016/j.lanwpc.2022.100341.

[24] Khatri, P., & Singh, A. (2025). App-delivered CBT integrated with primary-care workflow reduces antibiotic seeking for respiratory symptoms: randomized controlled effectiveness trial. *Journal of Medical Internet Research, 27*, e35822. https://doi.org/10.2196/35822.

